AFRL-AFOSR-UK-TR-2013-0037

Pressure Gain Combustion for Gas Turbines

Robert J. Miller
J. Heffer

University of Cambridge
Research Services Division
The Old School
Cambridge CB2 1TN
UNITED KINGDOM

EOARD Grant 10-3098

Report Date: August 2013

Final Report for 20 September 2010 to 19 January 2013

Distribution Statement A: Approved for public release distribution is unlimited.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
20 August 2013	Final Report	20 September 2010 – 19 January 2013

4. TITLE AND SUBTITLE

Pressure Gain Combustion for Gas Turbines

5a. CONTRACT NUMBER

FA8655-10-1-3098

5b. GRANT NUMBER

Grant 10-3098

5c. PROGRAM ELEMENT NUMBER

61102F

6. AUTHOR(S)

Robert J. Miller
J. Heffer

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cambridge
Research Services Division
The Old School
Cambridge CB2 1TN
UNITED KINGDOM

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515
APO AE 09421-4515

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/AFOSR/IOE (EOARD)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-AFOSR-UK-TR-2013-0037

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This final technical report consists of two interim progress report received from the grantee in Nov. 2011 and Sept. 2013.

Pressure gain combustion has the potential to increase gas turbine efficiency by more than 10%. There is gap in the technology necessary for such improvements. Namely, conventional turbines do not work efficiently in the unsteady flow produced by pressure gain combustors. This effort was to examine the problem using simplified experiments and numerical simulations to reveal the fundamental fluid mechanics of these unsteady flows. Specifically investigated were the effects of the geometry, jet Mach number, frequency, and temperature.

15. SUBJECT TERMS

EOARD, Pressure Gain Combustion, turbine engines

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18, NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Gregg Abate
UNCLAS	UNCLAS	UNCLAS	SAR	24	**19b. TELEPHONE NUMBER** *(Include area code)* +44 (0)1895 616021

November 2011 Progress report: Pressure Gain Combustion for Gas Turbines

J Heffer and R Miller

1 Abstract

Pressure gain combustion has the potential to increase gas turbine efficiency by more than 10%. There is gap in the technology necessary for such improvements, conventional turbines do not work efficiently in the unsteady flow produced by pressure gain combustors. We will examine the problem using simplified experiments and numerical simulations to reveal the fundamental fluid mechanics of these unsteady flows. Specifically we investigate the effects of the geometry, and jet mach number, frequency and temperature. So far the experiments have revealed some important effects as the mach number of the jet is changed. This project will end in September 2012 with a fuller understanding of the fluid mechanics and an informed design of the first stage turbine downstream of a pressure gain combustor.

2 Introduction

The aim of this project is to investigate how a pressure gain combustor should be integrated with turbomachinery inside a gas turbine. The efficiency of conventional gas turbines is limited by their use of constant pressure (in reality pressure loss) combustors. Substituting for a pressure gain combustor changes the thermodynamic cycle and allows for a step change in cycle efficiency. The technology behind achieving a combustion driven pressure gain is maturing however little effort has been devoted so far into integrating the combustor with the rest of the engine. Pressure gain combustors are valuable because there is more available energy in the flow that leaves them than is contained in the exit flow from a conventional combustor. However the flow that leaves the combustor is very unsteady. Few people have studied the efficiency of axial turbomachinery in unsteady flows Daneshyar et al 1969 and Van Zante et al 2007 report loss of efficiency of at least 10% and 61.8% in such unsteady flows. It is also noted that there is not an accepted performance metric for turbines in unsteady flows, these numbers are not directly comparable. This project aims to investigate how an unsteady flow typical of a pressure gain combustor interacts with the first component in the downstream turbine using simplified geometry so that the fundamental physical mechanisms can be understood. This allow an informed redesign of the turbine to work efficiently with the unsteady exit flow from a pressure gain combustor. Successfully replacing a conventional combustor in a small gas turbine representative of the helicopter engine has the potential to increase efficiency by 10% or more, the potential gains in larger, higher pressure ratio engines is smaller but estimated to be 5% or more. Such potential gains would have enormous benefits in terms of cost savings and reduction in pollutant formation.

This project involves computational and experimental work to investigate unsteady flows interacting with simplified representations of the turbine downstream of the combustor. The project will conclude in September 2012 with a fuller understanding of the fluid mechanics involved and a validated numerical tool for predicting the performance of the turbine in unsteady flow. We also aim to devise a performance metric for unsteady turbines so that the performance can be compared in a rational manner.

3 Nomencalture

γ	Ratio of specific heats
η	Efficiency
Θ	Thrust augmentation
τ	Time Period
C_p	Heat Capacity at Constant Pressure
D	Diameter
F	Force
L	Length
m	Mass Flow Rate
P	Pressure
T	Temperature
w	Work
Subscripts	
0	Atmospheric
1	Stagnation at Inlet
2	Stagnation at Exit
E	Ejector
S	Static

4 Background

Since the invention of the gas turbine it has been recognised as a pressure gain combustion cycle could yield a superior efficiency to a constant pressure combustion cycle The biggest obstacle to the implementation has been the fact that to achieve a pressure gain the combustion process must be unsteady. Generally this leads to the turbine receiving a highly unsteady flow which can reduce turbine efficiency and mechanical life. Many different types of pressure gain combustor have been proposed three of the most common are: the pulse combustor the pulse detonation engine and the wave rotor. The work in this project is principally concerned with pulse detonation engines and pulse combustors which both produce high velocity unsteady jets. We next examine the literature which may inform us of the best method to maximise work extraction from the unsteady flow leaving a pressure gain combustor.

Several authors have attempted to build pressure gain combustors and measure a pressure gain these include: Gemman et al 1995, Kentfield et al 1977 and Porter 1958. All of whom were interested in both maximising the pressure gain and minimising the unsteadiness. Gemmen used a plenum downstream of the combustor to reduce unsteadiness however this also reduced the pressure gain, he achieved only 1.5%, Kentfield and Porter used ejector like geometries downstream of the combustor, these also reduced the unsteadiness in the exit flow however the overall pressure gain was higher at 4.5 and 8% respectively, suggesting the ejector retains more of the stagnation

pressure gain produced by the combustor. Ejectors are likely to be a key technology to enable the successful integration of pressure gain combustion into gas turbines. Heffer and Miller 2009 suggested that the first nozzle in a gas turbine should be designed like an ejector at inlet, initial studies suggest that up to 65% of the pressure gain can be retained at inlet to the first turbine rotor. There are significant gaps in the understanding of ejectors which will be discussed in section 4.1, we hope to address some of these deficiencies in this project.

It is also interesting to consider the literature of turbocharging internal combustion engines. It is generally recognised that it is possible to extract more work from the exhaust of an IC engine if the flow is directly coupled to the turbine rather than with a plenum in between the two which acts to make the flow more steady, e.g. Watson and Janota 1982. This is because there is more available energy in the unsteady flow than is available if the flow mixes in a plenum. It occurs despite the fact that there is a drop in turbine efficiency associated with the unsteadiness in the flow. If the pressure gain combustion is to be successfully integrated within the gas turbine is important to maximise the turbine efficiency in the unsteady flow. Many people have investigated unsteady flows in radial turbomachinery, few have looked the effects in axial machines, which tend to be more efficient in most gas turbine applications. Danyshire et al 1969 investigated an axial turbocharger designed for use downstream of a large diesel engine, they tested three turbine geometries the best experienced a drop in efficiency of 10%.

A few people have looked at the efficiency of turbines under flows representative of pressure gain combustors. Van Zante 2007 used computational methods to assess the performance of a turbine downstream of a pulse detonation engine and found a reduction in turbine efficiency of 61.8%. Suresh et al 2009 also used numerical computations and found turbine efficiencies between 70% and 85%, lower than that expected for modern turbomachinery. Heffer and Miller 2010 built a cascade to examine the performance of the first stage nozzle downstream of the flow representative of a pressure gain combustor, the unsteady flow created losses which offset the pressure gain resulting in a reduction in stagnation pressure downstream of the vane compared to the steady flow case. However the main loss mechanism was identified and mitigation strategies were suggested. The work undertaken in this project will lead to a better understanding of turbine performance in unsteady flows and hopefully the design of a turbine less sensitive to inlet flow unsteadiness of this type expected from a pressure gain combustor.

Suresh et al 2009 highlight some important points about turbine efficiency, from one simulation they calculate three different efficiencies, 71%, 81% and 85% using different definitions. It is important for future comparisons to find an accepted definition of turbine efficiency for unsteady flows. Their work provides a neat summary of the difficulties involved. This will be further discussed in section 7.

4.1 Ejectors

Ejectors are passive devices which increase the thrust produced by a given jet. An example is shown in Figure 1.

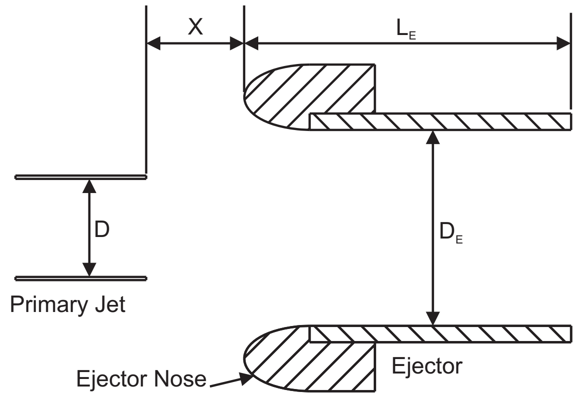


Figure 1 ejector schematic

The flow around the ejector induced by the primary jet creates an aerodynamic force on the ejector pulling it upstream, there is an equal and opposite increase in momentum of the jet. The figure of merit for an ejector is thrust augmentation ϴ.

$$\theta = \frac{F_{\text{Total}}}{F_{\text{Primary}}}$$

It was first noted by Lockwood that the thrust augmentation produced by ejectors driven by unsteady jet is significantly greater ϴ=1.4-2, than could be achieved by steady jets ϴ-1.1-1.3. Since then many works have been published which aim to experimentally optimise ejector performance, but few were able to offer insight as to the reasons behind the superior thrust augmentation offered by unsteady ejectors. Heffer et al 2008 were able to identify the key fluid mechanisms responsible for thrust augmentation and explain some of the observed experimental trends. It was shown that the operation of unsteady ejectors can be divided into two distinct phases, in the first the vortex ring which is formed from the unsteady jet hits the front of the ejector, see Figure 2, accelerating the fluid within it. This phase contributes very little to overall thrust augmentation, in the second phase, see Figure 3, ambient fluid is entrained into the ejector, the flow of entrained fluid creates a pressure around the ejector nose, which is responsible for creating most of the thrust augmentation.

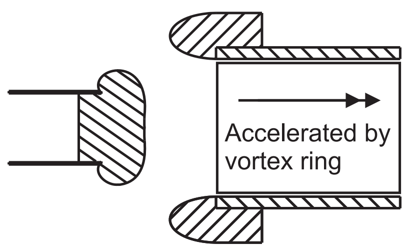


Figure 2 phase 1

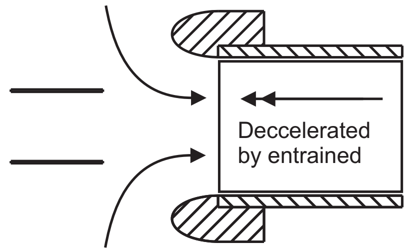


Figure 3 Phase 2

this theory successfully explains the variation of thrust augmentation with the length to diameter ratio of each slugs of fluid emitted by the primary jet, L/D, which was seen by Paxson et al 2004 and Mason and Miller 2006. They showed thrust augmentation rise in approximately linear fashion between L/D =3-7. This occurs because in this range the relative duration of phase 2 increases with L/D, more fluid is entrained and more thrust augmentation is created. However this work only considered isothermal jets at relatively low mach numbers, where compatibility effects are negligible. Significant variations in performance has been observed as the nature of the jet used to drive the ejector is changed. Lockwood 1964 showed this in his early work by varying the fuel flow to the pulse jets used to drive the ejector, this has the effect of simultaneously changing the jet velocity, temperature and frequency, therefore it was not possible to determine how each of these quantities effects the ejector performance. Since then different performances have been reported for similar ejectors driven by different jets and authors using different jets have reported different optical geometries. Mason 2006 reports that the same ejector produced a maximum thrust augmentation of 1.4 when driven by low Mach number isothermal jet, but 1.65 when driven by a pulse jet, even for the same L/D. Wilson et al 2005 found optimum ejector lengths of L_E/D =12 Using pulse detonation engine drivers, which have a very hot jet , that high Mach number ~5, and large L/D. Mason and Miller 2006 found an optimal L_E/D = 2, using low Mach number isothermal jets. In this project we aim to investigate how primary jet Mach number and temperature affect the fluid dynamics inside the ejector, and how this determines thrust augmentation. Additionally it has been reported by Hoke at al 2008 the performance of the ejectors driven by multiple jets show distinct differences from those driven by a single jet. In a real engine it is likely that the multiple combustors will be used is important to understand if there are these interaction effects between multiple jets.

5 Experimental Methods

Two different experiments are planned, one to look at the performance of ejectors, the other looks at the performance of nozzles interacting with unsteady jets. The unsteady jets will be provided in both cases by a siren valve. First the siren valve is discussed, then the two experimental set-ups.

5.1 Siren Valve

A siren valve is used to create the unsteady jets for the experiments. The siren valve is a mechanically simple device. A schematic is shown in Figure 4. High pressure air is supplied to one side of the disc. As the disc rotates the holes periodically allow flow to pass, this creates an unsteady jet. By varying the supply pressure to the valve it should be possible to change the Mach number of jets produced, it is also be possible to change the frequency, by changing the motor speed and the form of the jet can be changed by altering the shape and position of holes within the disc. The temperature of the jet can be altered by heating the air upstream of the valve.

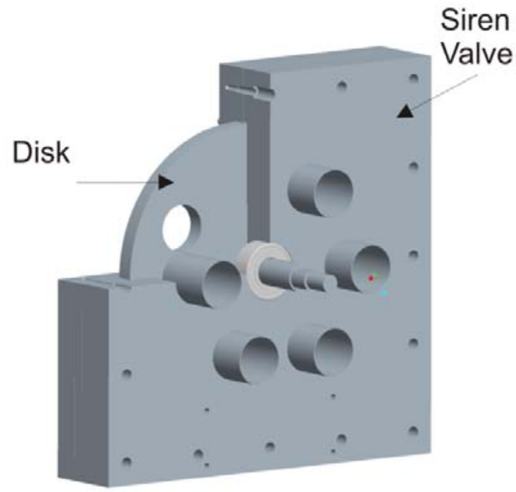


Figure 4 Siren Valve

During initial testing it was found that the unsteady jet produced by the siren valve was not satisfactory. The design intent was for the valve to produce a jet where the exit velocity was zero for some of the cycle. It was found that flow leakage around the disc meant that the velocity never reached zero. Teflon seals were introduced which significantly reduced the clearances inside the valve, this was successful to some degree however the variation of velocity over time from the jet is not as designed. Unsteady pressure transducers were used to measure the stagnation pressure profile of the jet over time, from these the velocity profile can be inferred. An example is shown in Figure 5.

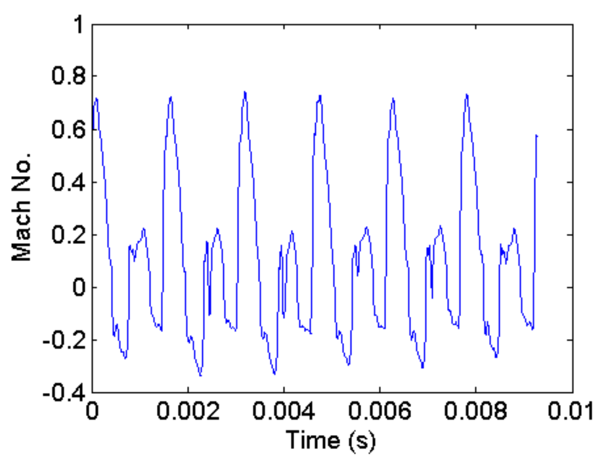


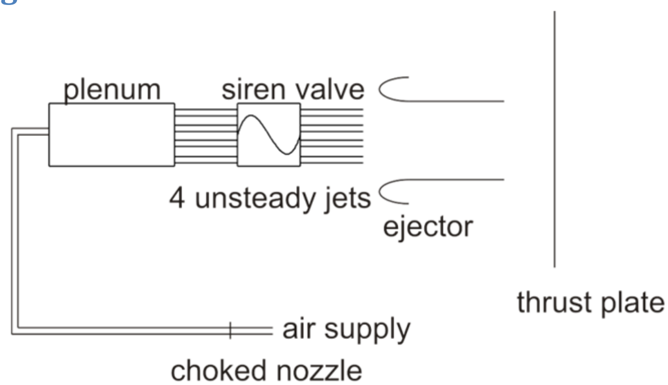
Figure 5 Mach number variation for unsteady jet

The jet produced by the siren valve has a series of high velocity peaks but between these much weaker pulses are produced, ideally there would be none. It is unclear exactly how this affects the results to be presented later. The Mach numbers in figure 5 were calculated from measured stagnation pressure data at the end of the tube, according to the equation below.

$$M^2 = \frac{2}{\gamma - 1}\left(\left(\frac{P_s}{P_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)$$

In the above equation it has been assumed that the static pressure is constant and equalled atmospheric pressure, this is not necessarily true but it was shown to be a good approximation by Heffer 2010. Schlieren photography was used to visualise jet, this showed qualitative agreement with the velocity data.

5.2 Ejector Rig

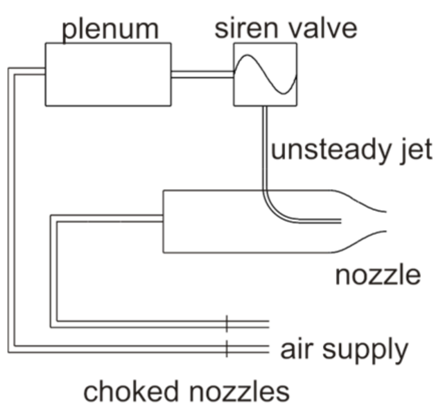


The ejector rig is designed to measure the performance of unsteady ejectors. Different ejector geometries can be tested, with up to 4 primary jets. The thrust augmentation can be determined because the total thrust is measured by a load cell attached to the thrust plate, and the force on ejector is measured by another load cell.

$$\theta = \frac{F_{\text{Thrust Plate}}}{F_{\text{Thrust Plate}} - F_{\text{Ejector}}}$$

Additionally the total mass flow supplied to the siren valve is measured by a choked orifice. The unsteady pressures upstream and downstream of the siren valve are also measured.

5.3 Nozzle Rig

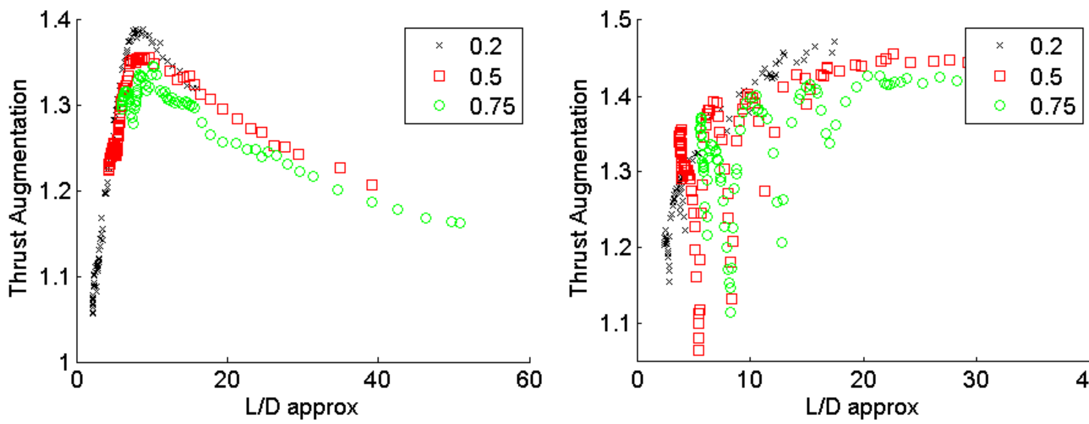


The nozzle rig was designed to measure how much of the stagnation pressure in an unsteady jet was retained at exit of a simple nozzle. A schematic of the rig is shown above, an unsteady jet is

positioned upstream of the nozzle to simulate the pressure gain combustor, a bypass flow is also simulated which would be needed in real engine to cool the products of combustion. Since its design it has been found that the siren valve will not produce the desired unsteady jets with the current setup. Originally it was planned to have a pipe approximately 10 inches long which ducted the unsteady flow from the siren valve in front of the nozzle. It has since been found that the siren valve only produces the desired flow if very short pipes are used. The experiment needs to be redesigned to accommodate this.

6 Ejector Performance

The performance of an ejector has been measured at a number of frequencies and Mach numbers, the length of the ejector was also varied in these tests. The results are shown below.



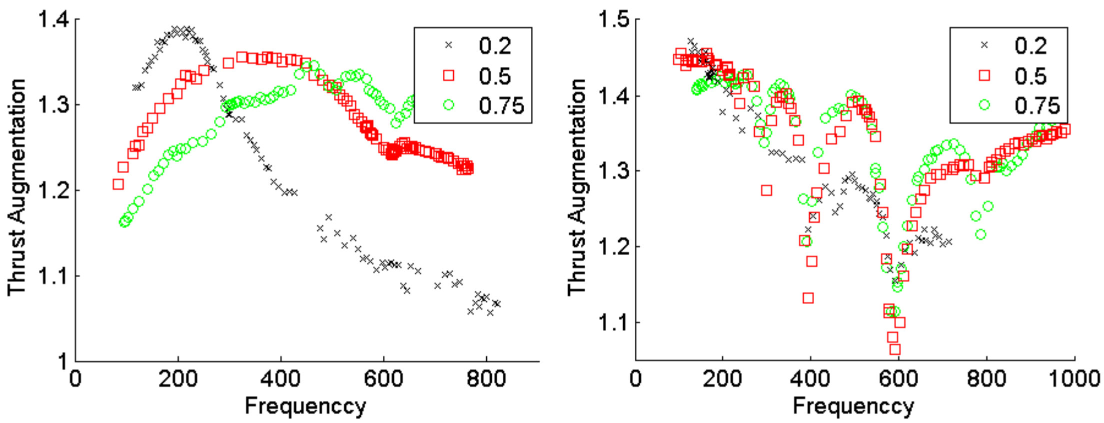
(a) $L_E/D = 4$ (b) $L_E/D = 10$

Figure 6 thrust augmentation vs L/D for different Mach numbers

Figure 6 shows how thrust augmentation varies with L/D for a long ejector and a short ejector. The data for the shorter ejector agrees well with the trends observed by Mason and Miller 2006 and by Paxson et al 2006. For the shorter ejector thrust augmentation data collapses reasonably well. The thrust augmentation is almost solely determined by L/D. Increasing Mach number reduces thrust augmentation by a small amount. Further work is needed to properly assess this trend, it is logical to assume that as the pressure ratio across the siren valve is raised to increase the Mach number the leakage across the siren valve rises too. Therefore the difference in thrust augmentation may be caused by leakage effects not because of the variation in Mach number. The Mach number has been changed over a relatively large range, compressibility effects are negligible at Mach 0.2 but important at Mach 0.75 with little influence on ejector performance.

The data for the longer ejector shows that the thrust augmentation cannot be said to be only a function of L/D. There are a number of important differences, there are a number of regions where distinct reductions in thrust augmentation are seen. Figure 7 plots the same thrust augmentation data against frequency of the driver jet, it is seen that these drops in thrust augmentation correspond to specific frequencies not L/Ds. This suggests some form of acoustic resonance is responsible. This is similar to the findings of Paxson et al who found that thrust augmentation peaked when the ejector length corresponded to acoustic frequency which was a non-integer multiple of the driver jet frequency.

If the drops in thrust augmentation are ignored an envelope of thrust augmentation vs L/D results. This shows that for longer ejectors thrust augmentation in general is higher as L/D increases, for shorter ejector is there is a definite peak around L/D=7. This may explain why Mason and Miller 2006 found an optimal ejector length shorter than that found by Paxson 2006, the driver jets they were using tended to produce jets of shorter or longer L/D respectively.



(a) $L_E/D = 4$ (b) $L_E/D = 10$

Figure 7 thrust augmentation vs frequency

Although the driver jet in this experiment has presented some problems, it is capable of producing flows over a very large range of nondimensional parameters. It is shown that for jets with a low L/D, shorter ejectors are likely to be optimal whereas longer ejectors are necessary for jets with higher L/Ds. The model proposed by Heffer et al 2008 to explain the fluid dynamics of ejectors shows that the cycle of operation is broken down into two phases. In the first phase of the unsteady jet accelerates the fluid inside the ejector. The thrust augmentation is created in the second phase when ambient fluid is entrained into the ejector. The thrust augmentation can be expressed as a function of the impulse of each slug of fluid from the primary jet and the impulse it produces on the ejector. It can be shown that the maximum impulse which can be generated on the ejector is equal to the momentum of the fluid within the ejector at the start of the entrainment phase. The momentum of that fluid contained within the ejector is a function its mass and velocity. It's velocity cannot be higher than that of the driver jet, therefore the total impulse produced is limited by the mass of fluid inside the ejector. If the total momentum of each slug of fluid is larger than this limit the short ejector will not produce large thrust augmentations. It is hoped that future detailed measurements of the time resolved pressure within the ejector will be able to prove or disprove this theory and also explain the fluid mechanism responsible for the drops in thrust augmentation at certain frequencies.

7 Performance Metric

The turbine efficiency is the ratio of the actual work output to an ideal work output, whilst the actual work output is relatively easy to measure the ideal work output is the subject of much debate. The simplest textbook definition to the efficiency involve uniform flow at turbine inlet and exit, both of which are time invariant. The isentropic efficiency is then given by:

$$\eta = \frac{work\ out}{\dot{m}C_pT_1\left(1-\frac{P_2}{P_1}\right)}$$

However in reality it is unlikely that the flow is uniform in space or time. It is difficult to extend the above definition to flows that are non-uniform because the pressure and temperatures no longer have single values

When considering fluid flows that vary in time the situation is considerably more complex. Daneshyar et al 1969 defined cycle average efficiency as:

$$\eta = \frac{work\ out}{\int_0^\tau \dot{m}C_pT_1\left(1-\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right)dt}$$

Simply the integral over one cycle of the instantaneous value of the steady state definition of efficiency. Palfreyman and Martinez-Botas 2005, extended this to include the fact that a particle will enter the turbine at a stagnation pressure $P_{01}(t)$ and leave at a different pressure at a later time $P_{02}(t+\delta t)$. Their definition of efficiency was therefore:

$$\eta = \int_0^\tau \left(\frac{work\ out}{\dot{m}C_pT_1\left(1-\left(\frac{P_2(t+\delta t)}{P_1(t)}\right)^{\frac{\gamma-1}{\gamma}}\right)}\right)dt$$

The integrand was turned the instantaneous efficiency, it was often found that this value exceeded one. Efficiency exceeding unity suggests a violation of some physical law, in fact the definition is flawed because the instantaneous work output is a function of the instantaneous flow round turbine, not a function of the flow at arbitrary inlet and exit points. In an effort to correct the definition two philosophies for the determination of δt were proposed, firstly that it should correspond to an acoustic timescale across the turbine and secondly it should correspond to convective timescale. In reality neither of these proposals was satisfactory, because there are many physical processes by which work is exchanged in the turbine, some corresponding to acoustic timescale is and others to convective. A further theoretical objection is that in some turbines there may be considerable accumulation of mass within the control volume which is not accounted for in such definitions of efficiency. It is the author's opinion that such instantaneous efficiencies have little physical justification and are of little practical importance for three reasons: generally only the cycle averaged work output is of importance (although mechanical considerations may require some knowledge of variation of output torque), it is rarely possible to measure all quantities with sufficient time resolution to get an accurate number and finally the motivation for knowing and instantaneous efficiency is likely to be to eliminate undesirable physical processes. This presumably would require a knowledge of the flow field, such knowledge would highlight the undesirable physical processes without having calculated any such efficiency.

The author proposes a different approach, the isentropic efficiency can be thought of as asking how close is a real machine to an ideal machine operating between two prescribed points. An alternative definition is to consider a particular flow having potential to do work the efficiency

defines how much work can a given machine extract from this flow and secondly is their potential to extract more from the exit flow. We define an efficiency based on the difference in the maximum work available at inlet and exit of the turbine. This leads to an efficiency based on the work potential flow, the amount of work that can be extracted via isentropic expansion, i.e. without using heat engines.

$$w = \oint C_p T \left(1 - \left(\frac{P_0}{P}\right)^{\frac{\gamma-1}{\gamma}} \right) dm$$

The efficiency is then defined as total work output produced by the turbine in one period divided by the difference in the work potential of flow that leaves to that which enters the turbine.

$$\eta = \frac{\oint work\ output}{\oint C_p T_1 \left(1 - \left(\frac{P_0}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \right) dm - \oint C_p T_2 \left(1 - \left(\frac{P_0}{P_2}\right)^{\frac{\gamma-1}{\gamma}} \right) dm}$$

For single stage turbines, or other occasions where it is impossible to usefully extract work or another benefit from the exit flow, the second term in the denominator should be removed, because none of this potential work will be realised. This is a similar rationale to the use of total-to-total or total-to-static isentropic efficiencies depending on how the exit flow from the turbine occurs.

The advantage of this definition is that it is thermodynamically rigourous, avoiding the consideration of instantaneous pressure ratios or pressure ratios with a time lag across the turbine. It is also unaffected by mass accumulation within the turbine so long as the flow is periodic. However it is noted that the efficiency of the turbine is then a function of the atmospheric pressure at which the flow ultimately leaves the machine. Figure 8 shows the variation of the new definition of efficiency with atmospheric pressure for a steady machine with a pressure ratio of two as it isentropic efficiency changes. In reality the choice of atmospheric pressure should be obvious in most situations. It is also noted that the new definition of efficiency tends to have a larger numerical value than isentropic efficiency. This is because any losses of mechanical energy in the flow result in viscous heating. This heating allows for more work to be extracted in downstream stages. The difference between the work potential at inlet and exit is therefore smaller than the maximum amount of work that can be extracted isentropically between the same pressure ratio and numerical value of efficiency is increased.

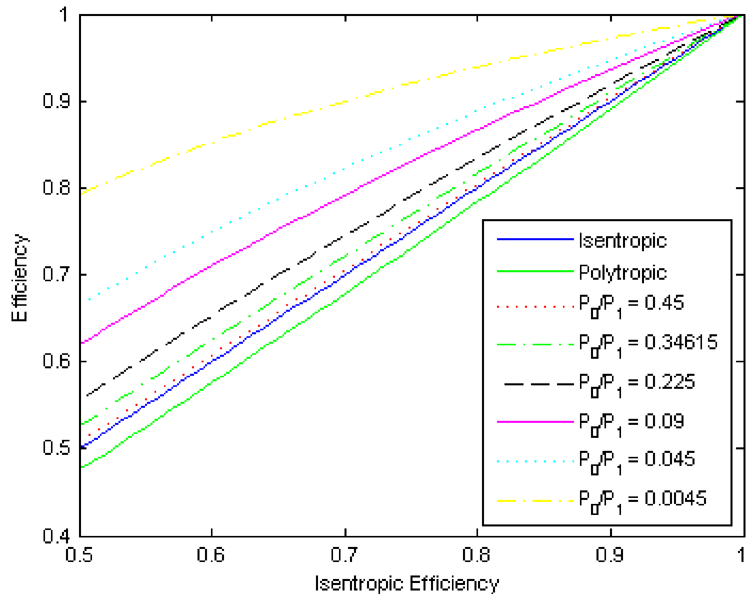


Figure 8 Variation of efficiency with P_0 forP_2/P_1=0.5

8 Conclusions

Experiments were undertaken to measure the performance of ejectors over a wide range of experimental conditions. A siren valve was used to produce the unsteady jet, slight issues remain about the jet's profile in time, however it was able to successfully produce unsteady jets over a much wider range of nondimensional conditions than has been produced before in any single experiment. The performance of the ejector was not very sensitive to Mach number. The performance generally reduced as Mach number was increased, this effect may have been caused by an unintended change in the jet. It was shown that the variation in the ejector performance with L/D was a strong function of ejector length with long ejectors generally performed better at high L/D. The performance of the ejector was also strongly influenced by acoustic resonances at specific frequencies, more work will be undertaken to understand this effect.

More work is necessary to improve the jet profile and to examine the performance of nozzles downstream of unsteady jets. Work is also going to simulate these flows numerically.

A new definition of efficiency has been proposed, the new definition eliminates many of the deficiencies identified by previous authors. It should provide a rational basis on which to assess turbine performance.

9 Bibliography

[1] Daneshyar, H., Edwards, K.J., Horlock, J.H., Janota, M.S., Pearson, R.D. and Shaw, R., 1969, ‘A comparison of the performance of three model axial flow turbines tested under both steady and pulse flow conditions’, Proc. Instn. Mech. Engrs., **184,** (61), pp.1119-1133

[2] Gemmen, R.S., Janus, M.C., Richards, G.A., Norton, T.S. and Rogers, W.A., 1995, 'Achieving improved cycle efficiency via pressure gain combustors', American Society of Mechanical Engineers Turbo Expo 1995

[3] Heffer, J., 2010, Integration of Pressure Gain Combustion with Gas Turbines, Ph.D. Thesis, University of Cambridge

[4] Heffer, J., Miller, R.. and Freeman, F., 2008 'The Time-resolved Flow within an Unsteady Ejector' 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, AIAA-2008-117

[5] Heffer, J. and Miller, R., 2009, 'Performance of Choked Unsteady Ejector-Nozzles for use in Pressure Gain Combustors' 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 5-8, AIAA-2009-1063

[6] Heffer, J. and Miller, R., 2010, 'A Transonic Vane for use Downstream of a Pressure Gain Combustor' 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 4-7, AIAA 2010-580

[7] Hoke, J., Bradley, R. and Schauer, F., 'Single-Ejector Augmentation of a Multi-Tube Pulsed Detonation Engine', 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 7-10, AIAA-2008-115

[8] Kentfield, J.A.C., Rehman, M. and Marzouk, E.S., 1977, 'A simple pressure-gain combustor for gas turbines', Journal of Engineering for Power, **99**, (2), pp.153-158

[9] Lockwood, R.M., 1959, 'Investigation of the process of energy exchange from an intermittent jet to an ambient fluid: summary report for the period 1 December 1958 to 30 June 1959', Report No. ARD-238, Tech. rep., Hiller Aircraft Corporation

[10] Lockwood, R. M., Patterson, W. G. & Beckett, J. E. 1964 Summary report on investigation of minature valveless pulsejets. Tech. Rep.. Hiller Aircraft Company.

[11] Mason, S.A., 2006, Pressure Gain Combustion for Gas Turbines, Ph.D. Thesis, University of Cambridge

[12] Mason, S.A. and Miller, R.J., 2006, 'The Performance of Ejectors Driven by Sinusoidally Unsteady Jets', 44th AIAA Aerospace Sciences Meeting and Exhibit 2006, AIAA 2006-1020

[13] Palfreyman, P. and Martinez-Botas, R., 2005, 'The Pulsating Flow Field in a Mixed Flow Turbocharger Turbine: An Experimental and Computational Study' J. Turbomach. 127, 144 (2005), DOI:10.1115/1.1812322

[14] Paxson, D.E. and Dougherty, K.T., 2005, 'Ejector enhanced pulsejet based pressure gain combustors: An old idea with a new twist', NASA/TM—2005-213854 AIAA-2005-4216

[15] Paxson, D.E., Wernet M.P. and Wentworth, T.J., 2004, 'An Experimental Investigation of Unsteady Thrust Augmentation Using a Speaker-Driven Jet', NASA/TM-2004-212909, AIAA-2004-0092

[16] Paxson, D.E., Litke, P.J., Schauer, F.R., Bradley, R.P. and Hoke, J.L., 2006, 'Performance Assessment of a Large Scale Pulsejet-Driven Ejector System', AIAA 2006-1021

[17] Porter, C.D., 1958, 'Valveless-gas-turbine combustors with pressure gain', ASME Paper No. 58-GTP-11, pp.179-184

[18] Suresh, A., Hofer, D.C. and Vangirala, V.E, 2009, 'Turbine Efficiency for Unsteady, Periodic Flows', 47th AIAA Aerospace Sciences Meeting 5-8 January 2009, Orlando, Florida, AIAA 2009-504

[19] Watson, N. and Janota, M., 1982, Turbocharging the internal combustion engine, MacMillan

[20] Wilson, J., Sgondea, A., Paxson, D.and Rosenthal, B., 2005, 'Parametric Investigation of Thrust Augmentation by Ejectors on a Pulsed Detonation Tube' AIAA–2005–4208

[21] Van Zante, D., Envie, E. and Turner, M., 2007, 'The Attenuation of Detonation Wave By an Aircraft Engine Axial Turbine Stage' NASA/TM-2007-214972

[22] Zheng, F., Kuznetsov, A., Roberts, W. and Paxson, D., 2009 'Numerical Study of a Pulsejet-Driven Ejector', 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 2-5 August 2009, Denver, Colorado, AIAA 2009-5185

September 2013 Progress report: Pressure Gain Combustion for Gas Turbines

J Heffer and R Miller

1 Abstract

Pressure gain combustion has the potential to increase gas turbine efficiency by more than 10%. There is gap in the technology necessary for such improvements, conventional turbines do not work efficiently in the unsteady flow produced by pressure gain combustors. Recent work in this project has focused on CFD to understand the fluid mechanics of the interaction of an unsteady jet with the first stage nozzle guide vane (NGV) and to design a new NGV which has improved performance in the unsteady flow field relative to conventional designs.

2 Introduction

The aim of this project is to investigate how a pressure gain combustor should be integrated with turbomachinery inside a gas turbine. The efficiency of conventional gas turbines is limited by their use of constant pressure (in reality pressure loss) combustors. Replacing a conventional combustor with a pressure gain combustor changes the thermodynamic cycle and allows for a step change in cycle efficiency. The technology behind achieving a combustion driven pressure gain is maturing however little effort has been devoted so far into integrating the combustor with the rest of the engine. Pressure gain combustors are valuable because there is more available energy in the flow that leaves them than is contained in the exit flow from a conventional combustor. However the flow that leaves the combustor is very unsteady. Few people have studied the efficiency of axial turbomachinery in unsteady flows Daneshyar et al 1969 and Van Zante et al 2007 report a loss of efficiency 10% and 61.8% respectively in such unsteady flows. This project aims to investigate how an unsteady flow typical of a pressure gain combustor interacts with the first component in the downstream turbine. This allow an informed redesign of the turbine to work efficiently with the unsteady exit flow from a pressure gain combustor. Successfully replacing a conventional combustor in a small gas turbine representative of the helicopter engine has the potential to increase efficiency by 10% or more, the potential gains in larger, higher pressure ratio engines is smaller but estimated to be 5% or more. Such potential gains would have enormous benefits in terms of cost savings and reduction in pollutant formation.

3 Background

Since the invention of the gas turbine it has been recognised that a pressure gain combustion cycle could yield a superior efficiency to a constant pressure combustion cycle. The biggest obstacle to the implementation has been the fact that pressure gain the combustion process generally this leads to the turbine receiving a highly unsteady flow which can reduce turbine efficiency and mechanical life.

Many different types of pressure gain combustor have been proposed three of the most common are: the pulse combustor, the pulse detonation engine and the wave rotor. The work in this project is principally concerned with pulse detonation engines and pulse combustors which both produce high velocity unsteady jets. We next examine the literature which may inform us of the best method to maximise work extraction from the unsteady flow leaving a pressure gain combustor.

Several authors have attempted to build pressure gain combustors and measure a pressure gain these include: Gemman et al 1995, Kentfield et al 1977 and Porter 1958. All of whom were interested in both maximising the pressure gain and minimising the exit flow unsteadiness. Gemmen used a plenum downstream of the combustor to reduce unsteadiness however this also reduced the pressure gain, he achieved only 1.5%, Kentfield and Porter used ejector like geometries downstream of the combustor, these also reduced the unsteadiness in the exit flow however the overall pressure gain was higher at 4.5 and 8% respectively, suggesting the ejector acts to retain more of the stagnation pressure gain produced by the combustor. Ejectors are likely to be a key technology to enable the successful integration of pressure gain combustion into gas turbines. Heffer and Miller 2009 suggested that the first nozzle in a gas turbine should be designed like an ejector at inlet, initial studies suggest that up to 65% of the pressure gain can be retained at inlet to the first turbine rotor.

Further insight can be gained by considering the literature of turbocharging internal combustion engines. It is generally recognised that it is possible to extract more work from the exhaust of an IC engine if the flow is directly coupled to the turbine rather than with a plenum in between the two which acts to make the flow more steady, e.g. Watson and Janota 1982. This is because there is more available energy in the unsteady flow than is available if the flow mixes in a plenum. It occurs despite the fact that there is a drop in turbine efficiency associated with the unsteadiness in the flow. If the pressure gain combustion is to be successfully integrated within the gas turbine is important to maximise both the available energy at inlet to the turbine and the turbine efficiency in the unsteady flow. Therefore it is likely that the best designs will have the turbine closely coupled with the combustor.

A few people have looked at the efficiency of turbines under flows representative of pressure gain combustors. Van Zante 2007 used computational methods to assess the performance of a turbine downstream of a pulse detonation engine and found a reduction in turbine efficiency of 61.8%. Suresh et al 2009 also used numerical computations and found turbine efficiencies between 70% and 85%, lower than that expected for modern turbomachinery. Danyshire et al 1969 investigated an axial turbocharger designed for use downstream of a large diesel engine, they tested three turbine geometries the best experienced a drop in efficiency of 10%. Heffer and Miller 2010 built a cascade to examine the performance of the first stage nozzle downstream of the flow representative of a pressure gain combustor, the unsteady flow created losses which offset the pressure gain resulting in a reduction in stagnation pressure downstream of the vane compared to the steady flow case. However a major loss mechanism was identified. It is clear that conventional turbomachinery will not work well and a redesign is needed if the turbine efficiency is to be maintained.

It is important that Heffer and Miller 2010 were able to identify specific loss mechanisms, because understanding the loss mechanisms should lead to improved designs. Their setup is shown in figure 1 which allowed the vane to be tested with three different inlet conditions; uniform upstream conditions, an unsteady jet upstream of the vane with a surrounding bypass flow (the bypass flow is

needed in a real engine because not all the air goes through the core combustor since the combustor air fuel ratio is richer than that of the overall engine) and a steady jet with a surrounding bypass flow (which is not representative of a real pressure gain combustor but allows much of the physics to be understood). They show that as the vorticity in the unsteady jet convects through the passage it is distorted and stretched. This causes large secondary flows and increased loss. The mechanism is illustrated in figure 2 below. This mechanism is shown more clearly in the case with a steady jet upstream of the vane than in the unsteady case, where distinct features cannot be seen in time average data. The stagnation pressure coefficient was measured downstream of the blade with a steady jet being blown into the passage. This is shown in figure 3, the secondary flow is clearly visible with low stagnation pressure fluid being mixed into the main stream by a large vortical structure.

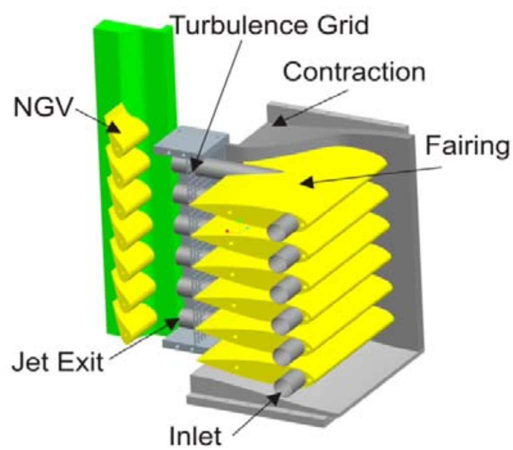


Figure 1 Experimental setup from Heffer and Miller 2010

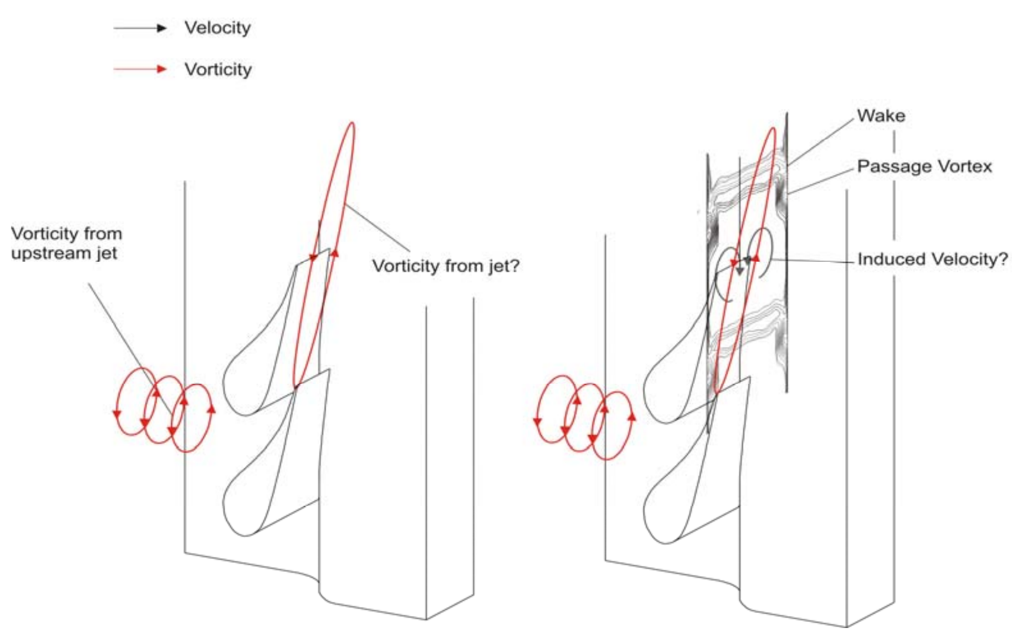


Figure 2 Schematic representation of vorticity evolution through NGV from Heffer and Miller 2010

4 CFD

Using CFD it is hoped that improved vanes can be designed and that the fluid mechanics can be better understood. We are using the turbomachinery specific codes TBlock written by John Denton and TurboStream, which is based on TBlock but upgraded to run on graphics processors giving a speed increase of 10x. The CFD will be pursued following the experiments of Heffer and Miller 2010 with both unsteady and steady jets upstream of the vane. First the vane geometry will be explored and optimised using a test case with a steady jet rather than an unsteady jet. This is because steady CFD is at least an order of magnitude faster than unsteady CFD. This will allow a much larger range of geometries to be tested. Secondly specific geometries will be tested under unsteady flow conditions, which will allow a better understanding of performance and flow physics.

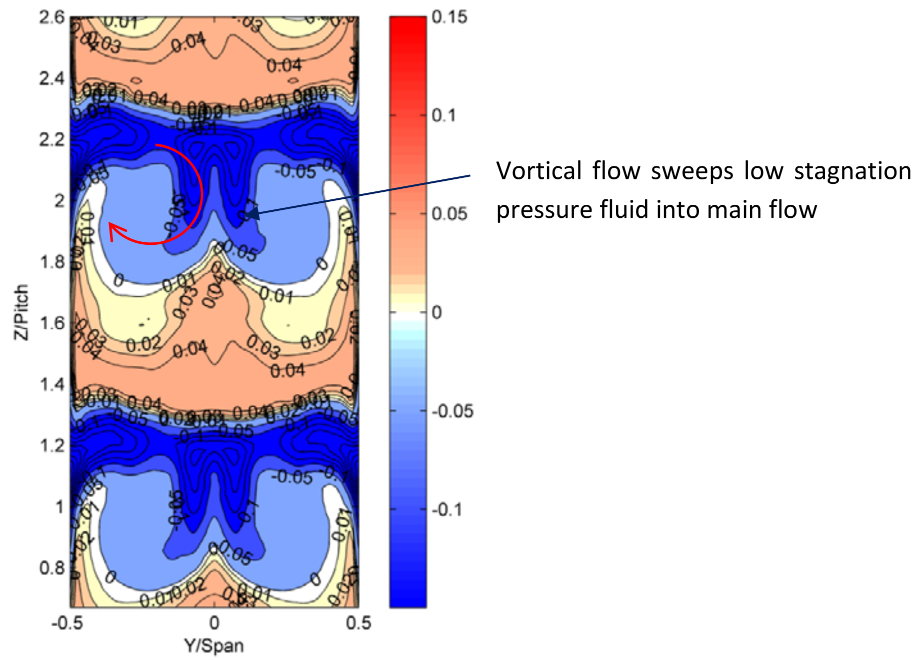


Figure 3 Exit stagnation pressure coefficient for datum blade with steady jet, measured experimentally by Heffer and Miller 2010

4.1 Geometry optimisation

First it is necessary to validate our CFD tool, this is done by modelling the experiments of Heffer and Miller 2010. The data from the experimental test case shown in figure 3 and can be compared to the numerical results shown in figure 4. The agreement is good, the pattern of secondary flow is qualitatively correct and the depths of the wakes agree.

With a validated tool it is possible to begin geometric optimisation. A key part of optimisation is parameterisation of the design space. For this study it was decided to focus on a simple parameterisation with a few physically meaningful parameters, this was done in the hope that it would yield more physical understanding than a more abstract parameterisation. The main geometric parameters will be the profile of flow turning, the profile of passage contraction both in the span-wise and pitch-wise sense, and the vane leading edge shape. Following this fully 3D geometries may be investigated. The first area of study is the vane turning profile. This was of

interest as previous work at Cambridge suggests that the profile of flow turning affects loss in vanes used with unsteady jets. This will be discussed as an example of our methodology.

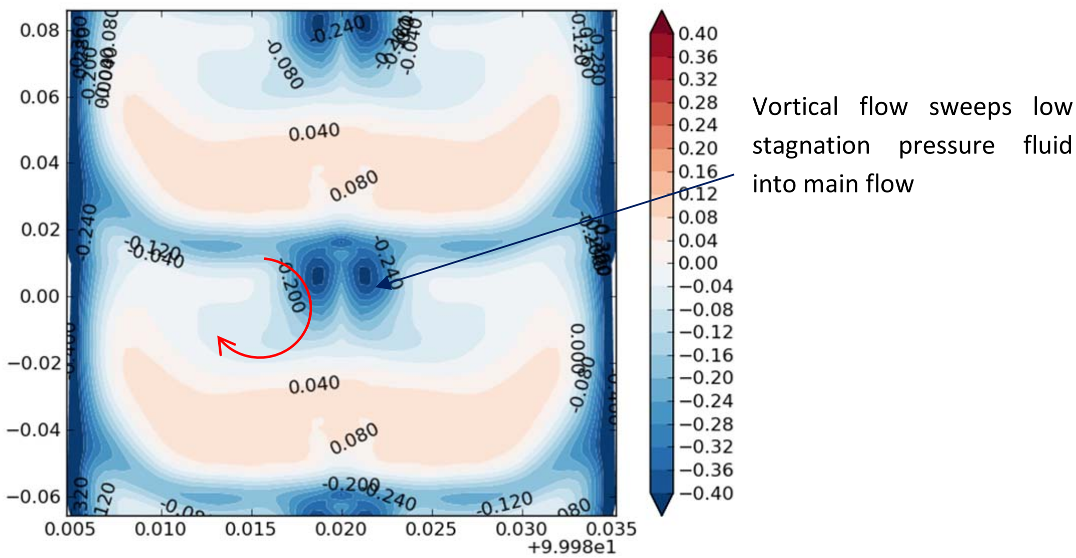


Figure 4 Exit stagnation pressure coefficient predicted by TurboStream for datum blade with a steady jet at inlet.

Figure 5 shows how the vane has been broken down into 3 parts, the inlet, the passage and the uncovered section (named as such because it is the region of uncovered turning). This decomposition of the blade allows the effects of turning to be investigated. The rate of flow turning in the passage can be changed with the rest of the blade held constant. The advantages of this approach are that the passage shape can be controlled by only a few parameters, i.e by fitting a smooth curve between the start and end with one or two control points, reducing the design space for an optimiser and secondly that all the designs will be aerodynamic, a free parameterisation would produce many potential designs that are obviously bad but would still take resources to be eliminated. However this approach may limit the range of possible designs. Initially the passage geometry has been varied by simply scaling the datum blade passage, keeping the inlet and uncovered regions constant.

Figure 6 shows a plot of the % of work potential destroyed in the passage. The work potential is the amount of work that can be extracted via isentropic expansion, i.e. without using heat engines, to a defined reference pressure:

$$w = \oint C_p T_0 \left(1 - \left(\frac{P_{ref}}{P_0} \right)^{\frac{\gamma - 1}{\gamma}} \right) dm$$

This is evaluated for a number of different passage lengths and for the case of a uniform inlet flow and the case of a steady jet being blow into the inlet. Although in uniform inlet case the performance gets worse as the passage is made longer, the case with blowing shows an initial improvement as the passage is made longer followed by a fall a then a rise. There is approximately an additional 50% of loss generated by the jet for the datum case, but about 1/4 of this increase can

be eliminated in a different design. Although this is not fully understood is shows that designs can be made more efficient by reducing the rate of turning in the passage. Work is ongoing to understand the physical reasons for this result. This redesign is very preliminary and it is hoped that with more work the additional loss due to the jet can be further reduced.

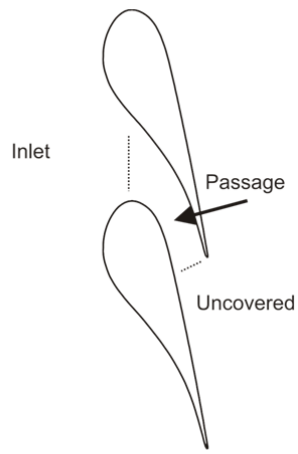


Figure 5 Schematic representation of the decomposition of the vane for optimisation.

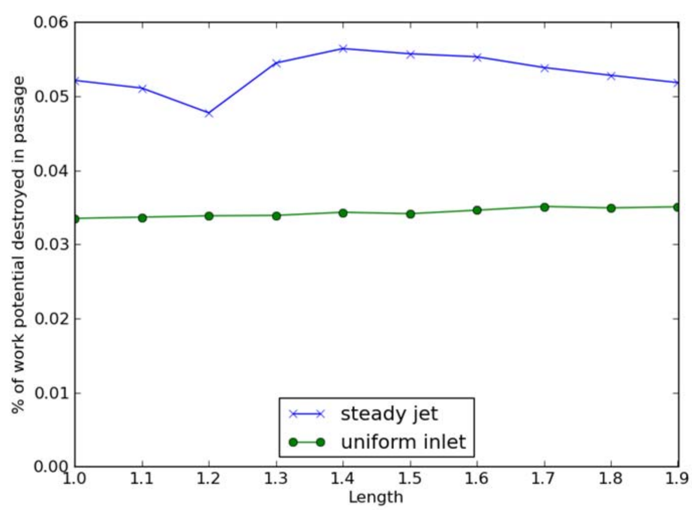


Figure 6 Vane efficiency as a function of passage length, where length is the multiplication factor relative to the datum blade.

4.2 Unsteady – Parallelised Code

It was expected that the unsteady boundary conditions needed would be included in TurboStream, the GPU solver. Unfortunately this has not happened, so the unsteady boundary conditions have been implemented in TBlock, essentially the same code put running on slower CPUs. This has been recently completed and is producing realistic looking data. Currently there is not a good

experimental test case to validate the jet alone; a simple experiment will be performed to validate the unsteady flow to check that the correct vortex rings are being developed.

5 Future Work

The next body of work will build on the CFD performed to date. A large amount of work has been invested to build meshes and find the appropriate methods to give good results. The two work packages of focusing on steady and unsteady jets will be pursued simultaneously. This will allow a large range of geometries to be explored rapidly. Detailed investigations into the flow should reveal specific areas of entropy generation that can hopefully be explained and eliminated by design modifications.

6 Conclusions

A numerical tool is being developed to simulate and optimise a nozzle guide vane interacting with the unsteady jet from a pressure gain combustor. The geometry will first be optimised for a steady jet blowing into the passage, then promising geometries will be run with an unsteady jet. So far the length of the passage has been varied, showing that the efficiency of the vane is affected by this parameter. It is shown that the steady jet increases losses by about 50% over the datum uniform inlet flow. However, ¼ of this additional loss has been removed by the first simple attempt at a redesign. The ease of finding this performance gain suggests more should be possible. Further tests are needed to determine how the rate of turning in the passage and other geometrical parameters affect performance. The unsteady jet has simulation has been developed and is giving promising results although further validation is needed.

7 Bibliography

[1] Daneshyar, H., Edwards, K.J., Horlock, J.H., Janota, M.S., Pearson, R.D. and Shaw, R., 1969, 'A comparison of the performance of three model axial flow turbines tested under both steady and pulse flow conditions', Proc. Instn. Mech. Engrs., **184,** (61), pp.1119-1133

[2] Gemmen, R.S., Janus, M.C., Richards, G.A., Norton, T.S. and Rogers, W.A., 1995, 'Achieving improved cycle

[3] Heffer, J. and Miller, R., 2010, 'A Transonic Vane for use Downstream of a Pressure Gain Combustor' 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 4-7, AIAA 2010-580

[4] Kentfield, J.A.C., Rehman, M. and Marzouk, E.S., 1977, 'A simple pressure-gain combustor for gas turbines', Journal of Engineering for Power, **99**, (2), pp.153-158

[5] Paxson, D.E. and Dougherty, K.T., 2005, 'Ejector enhanced pulsejet based pressure gain combustors: An old idea with

[6] Porter, C.D., 1958, 'Valveless-gas-turbine combustors with pressure gain', ASME Paper No. 58-GTP-11, pp.179-184

[7] Watson, N. and Janota, M., 1982, Turbocharging the internal combustion engine, MacMillan

[8] Van Zante, D., Envie, E. and Turner, M., 2007, 'The Attenuation of Detonation Wave By an Aircraft Engine Axial Turbine Stage' NASA/TM-2007-214972